

# Must Sgr A\* be a SMBH?

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&

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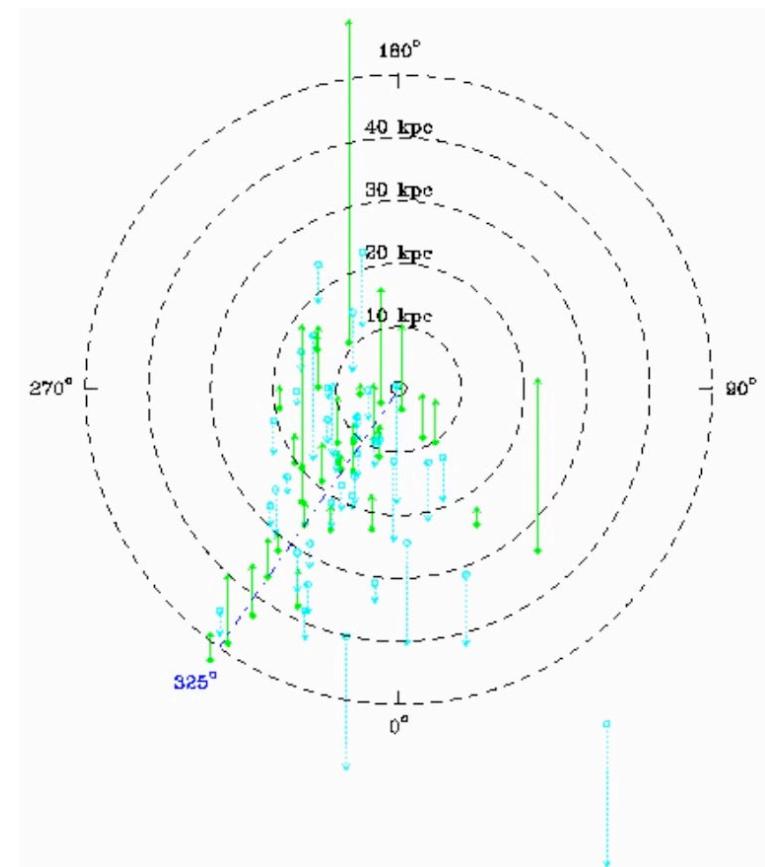
Rainer Schoedel

Andreas Eckart

Andreas Brunthaler

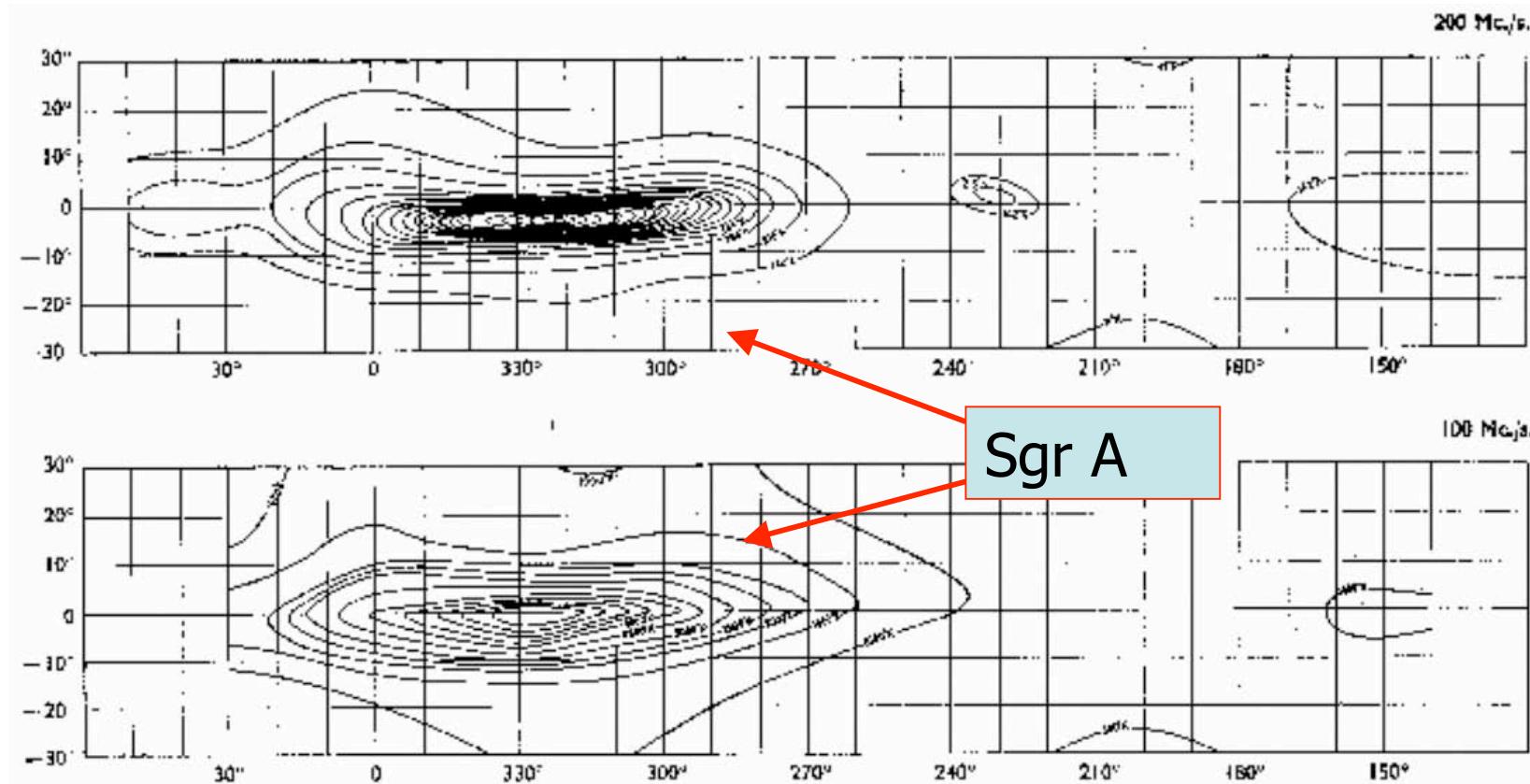
# Discovery of Galactic Center

- Shapley (1918):
  - Globular Clusters “point” to Galactic Center
- $R_o = 13 \text{ kpc}$



# Early Radio Observations

J. H. Piddington

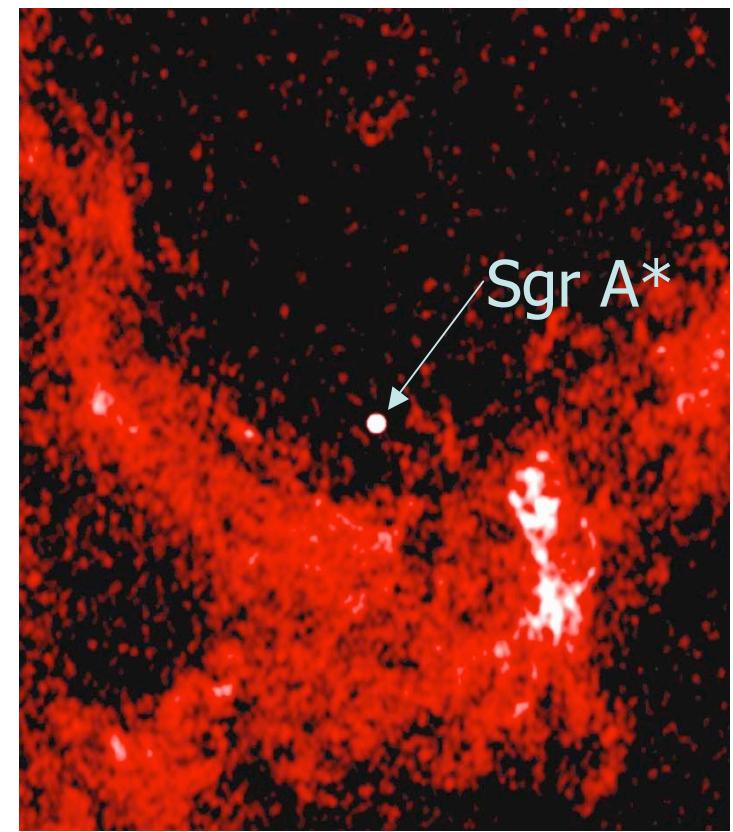
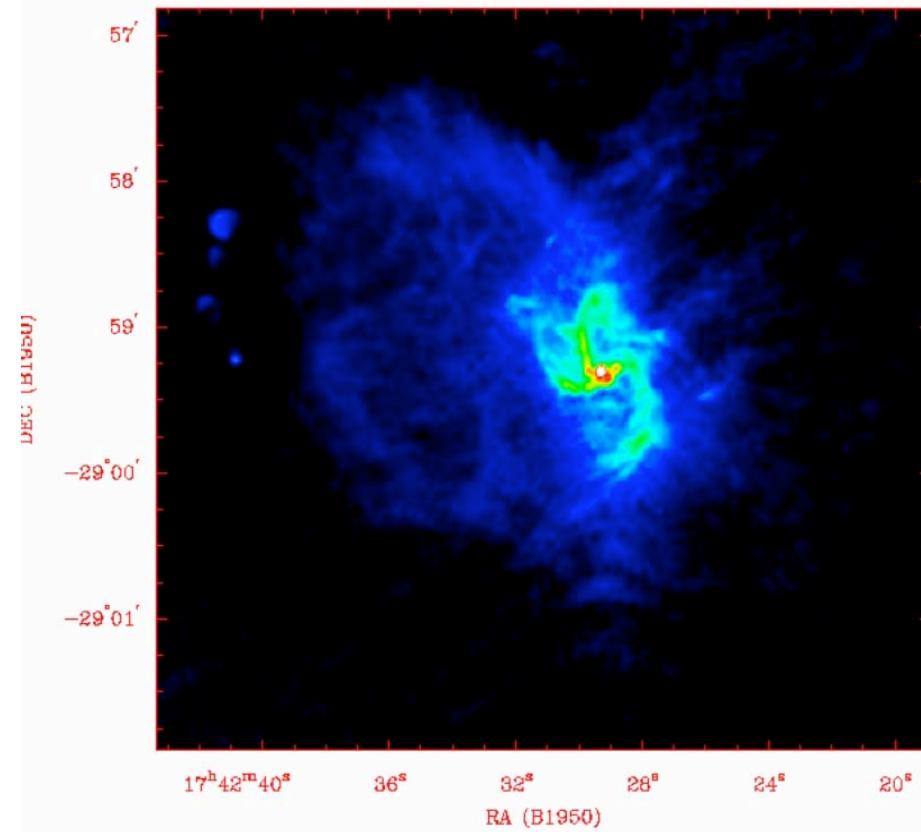


Piddington & Minnett (1951); Haddock, Mayer & Sloanaker (1954); McGee & Bolton (1954)

# Brief History of Sgr A\*

- Balick & Brown (1974) Discover Sgr A\*: “Intense Sub-Arcsecond Structure”
- Lo et al (1985) Sgr A\*  $< 20$  AU
- Backer et al (1993)  $< 3$  AU
- Rogers et al (1994)  
Krichbaum et al (1998)  $< 1$  AU  
Doeleman et al (2001)  
Bower et al (2004)

# VLA Images of Sgr A

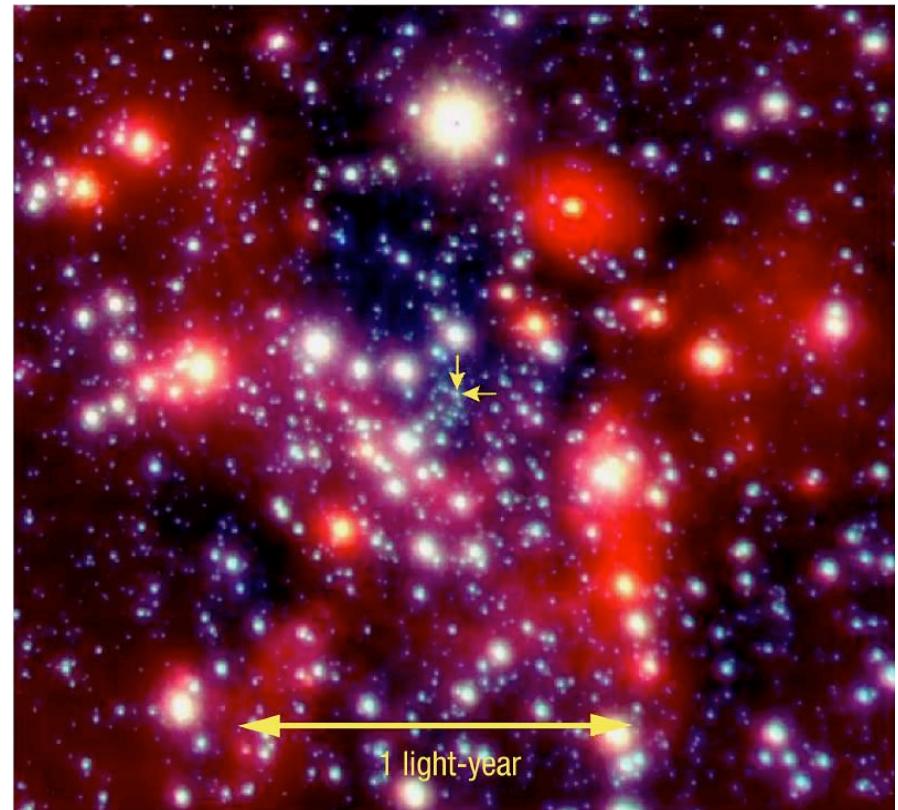


2005 September 1

J-H Zhao  
GLAST Symp.: Galactic Center

# IR Image of GC

- 1-3 um image
- Where is Sgr A\*?



The Centre of the Milky Way  
(VLT YEPUN + NACO)  
ESO PR Photo 23a/02 (9 October 2002)

© European Southern Observatory  


# 7 Questions:

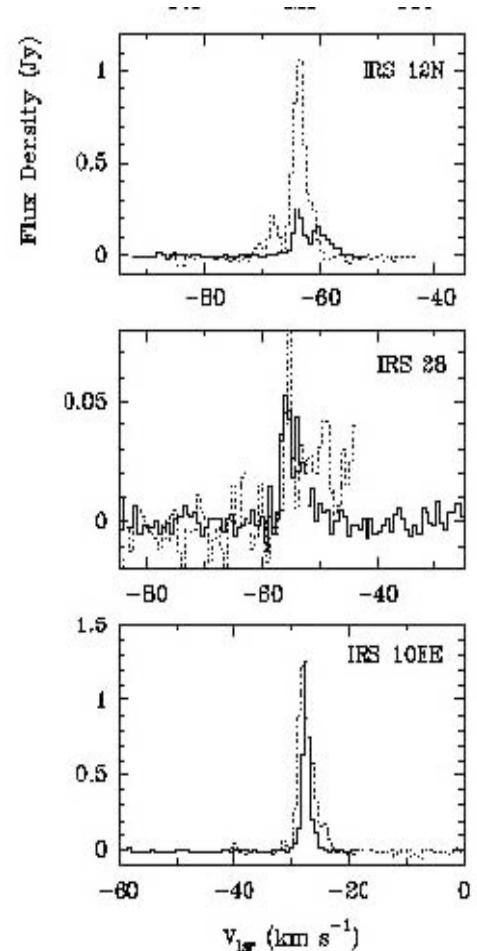
- Is Sgr A\* at the center of the stellar cluster?
- Is the stellar cluster tied to Sgr A\*?
- Is Sgr A\* at the dynamical center of the Galaxy?
- Does Sgr A\* have a peculiar motion?
- Does Sgr A\* have all the mass sensed by stars?
- Could exotic dark matter dominate the G. C. mass?
- Can intermediate mass black holes be in the G. C.?

# Radio/IR frame alignment

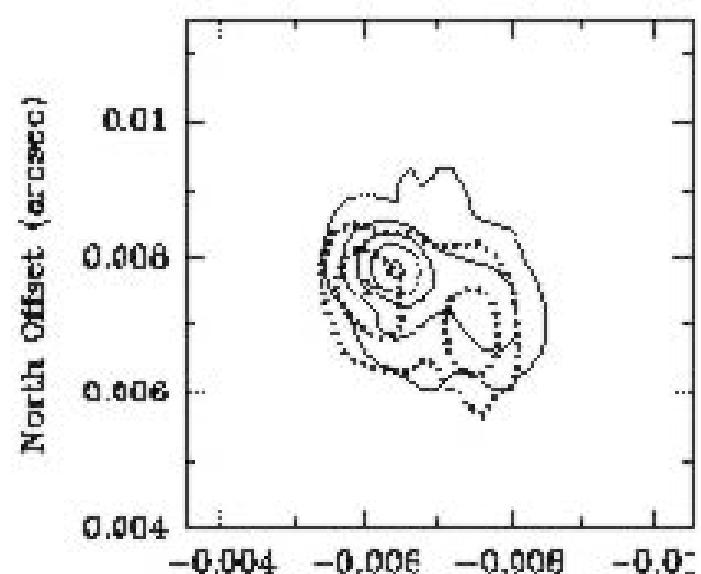
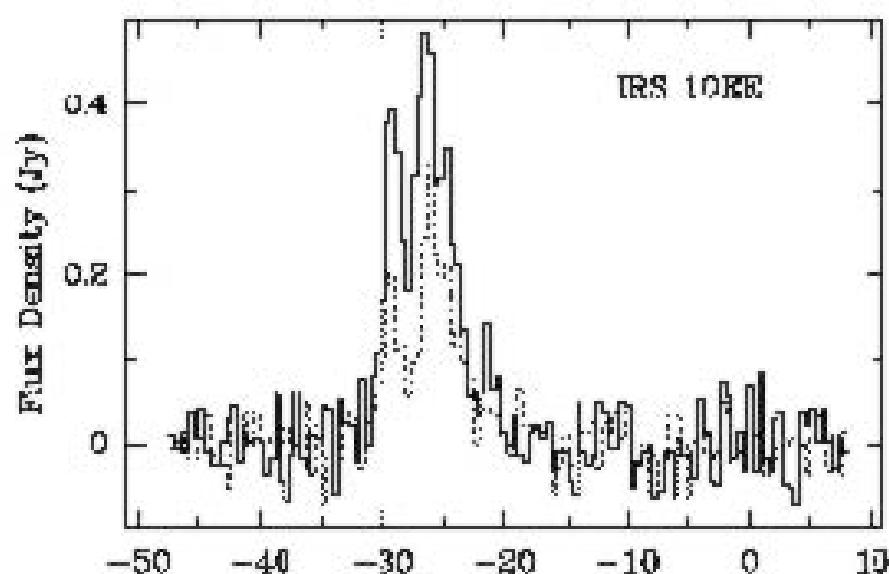
- Use stars visible in both Radio and IR:  
Red Giants with masers
- Compare Radio and IR positions:  
Solve for IR plate scale & rotation;  
Align IR with Radio to find Sgr A\*

# VLA positions for stars

- 7 SiO masers <12" of SgrA\*
- ~0.1 – 1 Jy
- Positions to ~ 3 mas
- mas/yr motions in few years



# VLBA proper motions

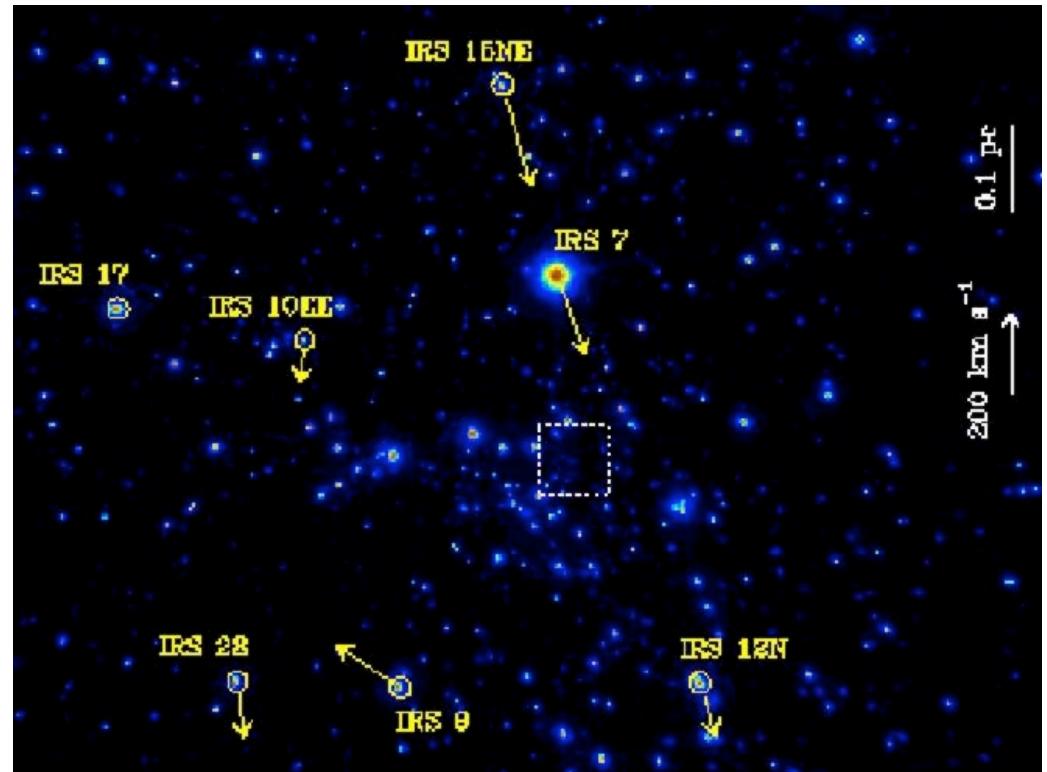


(Reid et al 2003)

- Sub-mas positions with respect to Sgr A\*
- mas/yr motions in 3 months

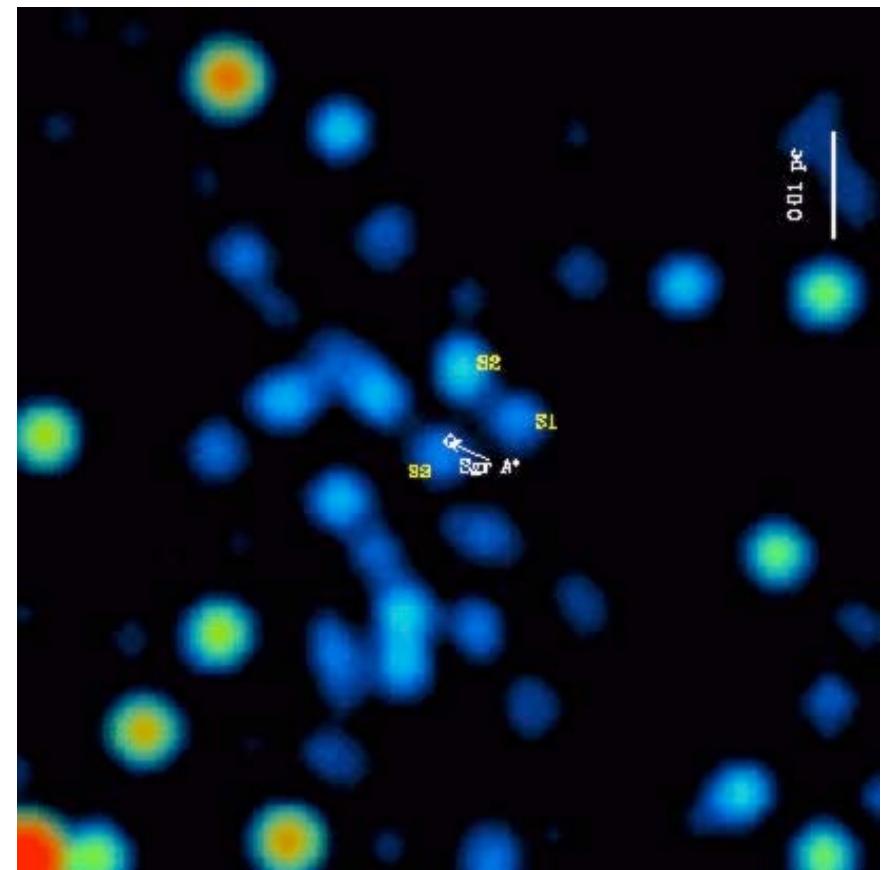
# Stellar positions & motions

- 7 SiO maser stars
- positions  $\sim 3$  mas
- motions  $\sim 50$  km/s



# Where was Sgr A\* in 1995

- 15 mas accuracy
- Between stars:  
S1, S2 & S3
- Sgr A\* < 9 mJy @  $2\mu$



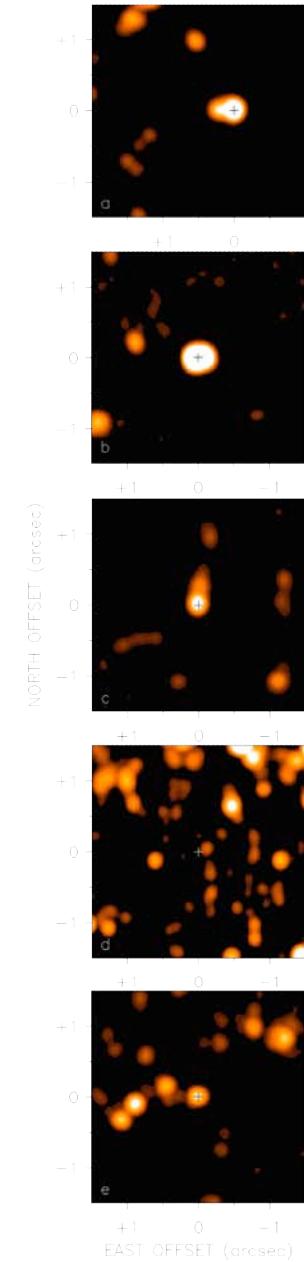
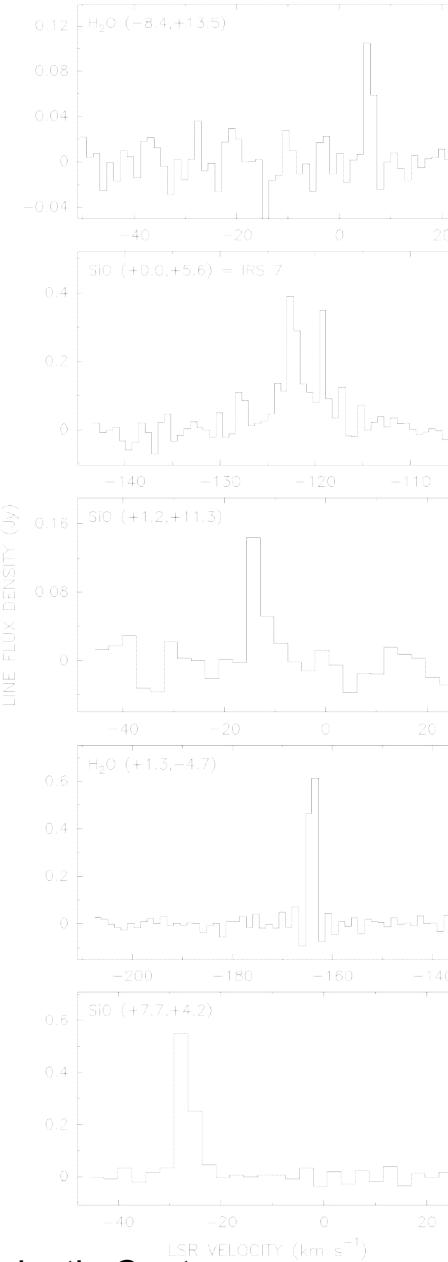
# Stellar or Star Forming Masers?

- SiO masers => Red Giant stars
- H<sub>2</sub>O masers either RG stars or star forming regions

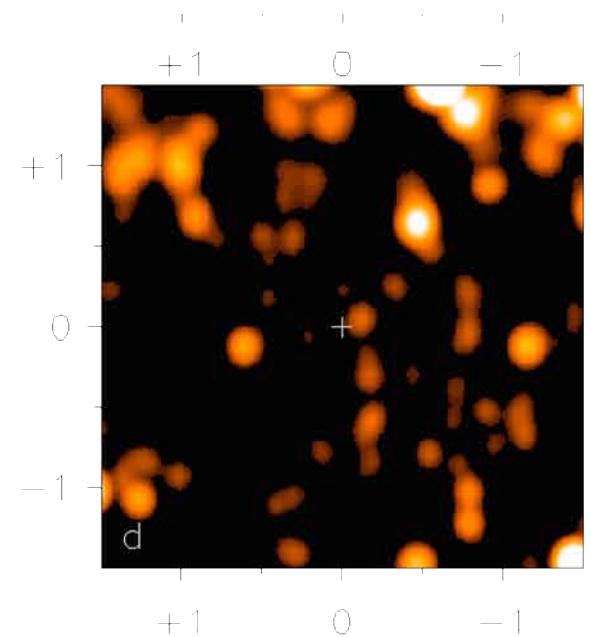
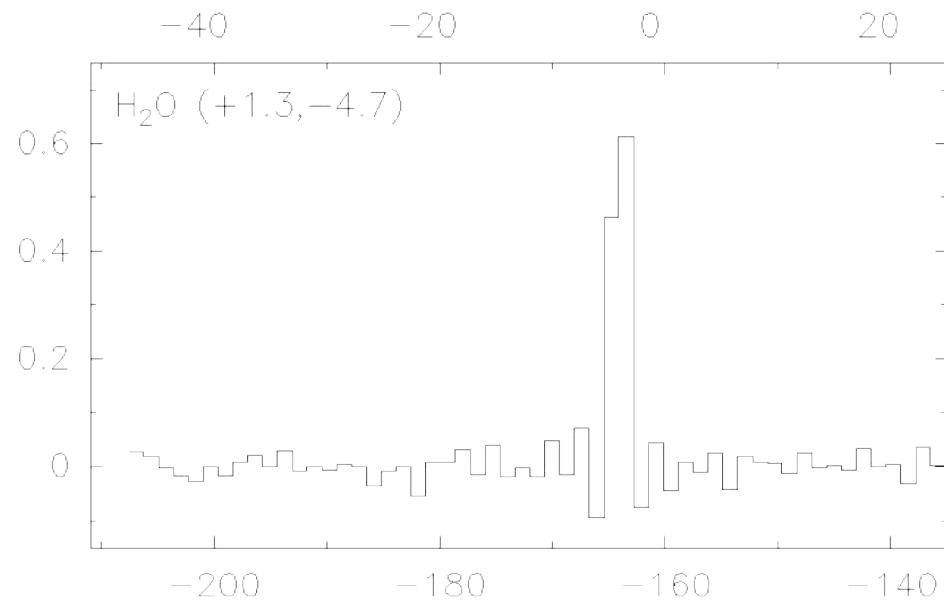
Menten, Reid, Eckart & Genzel (1997)

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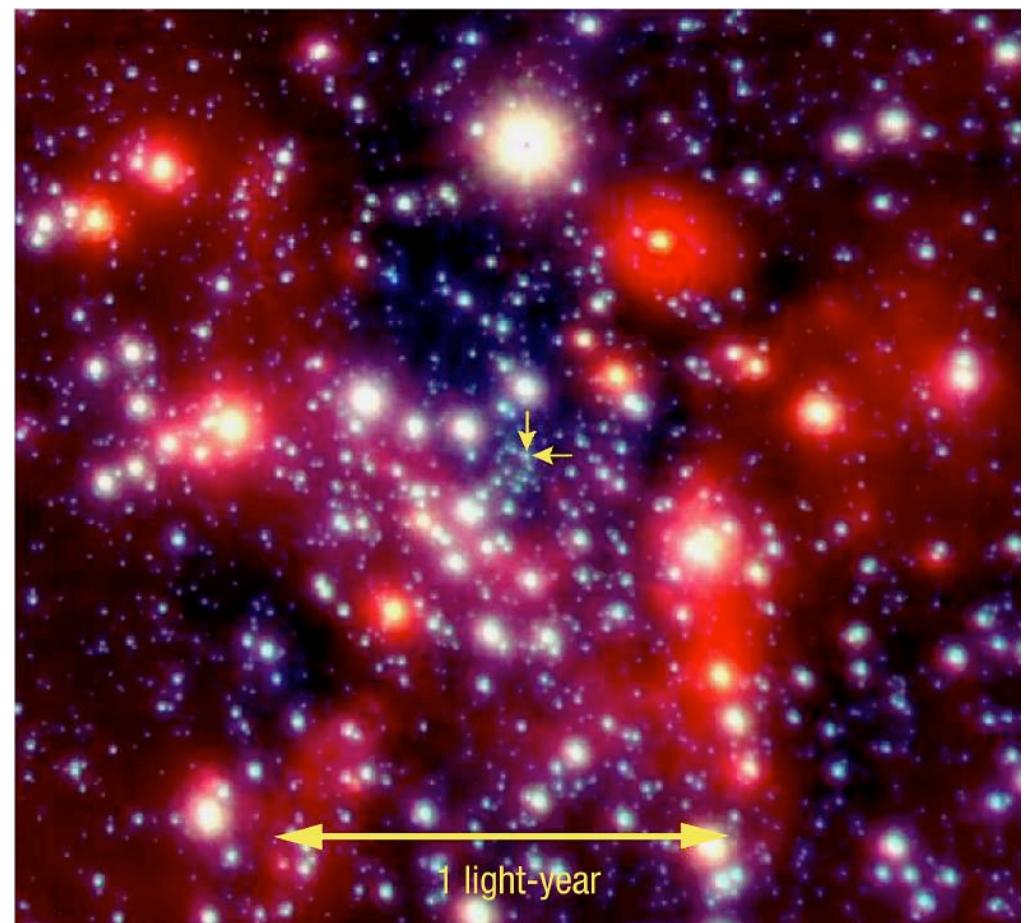
# Star Forming Region H<sub>2</sub>O Maser



- No IR source
- Projected only 5" (0.2 pc) from Sgr A\*
- V(LSR) = -165 km/s

# VLT with Adaptive Optics

- “3-color”: 1.5 - 3  $\mu\text{m}$
- 8.2 m VLT telescope
- CONICA (IR camera)
- NAOS (adaptive optics)
- 60 mas resolution

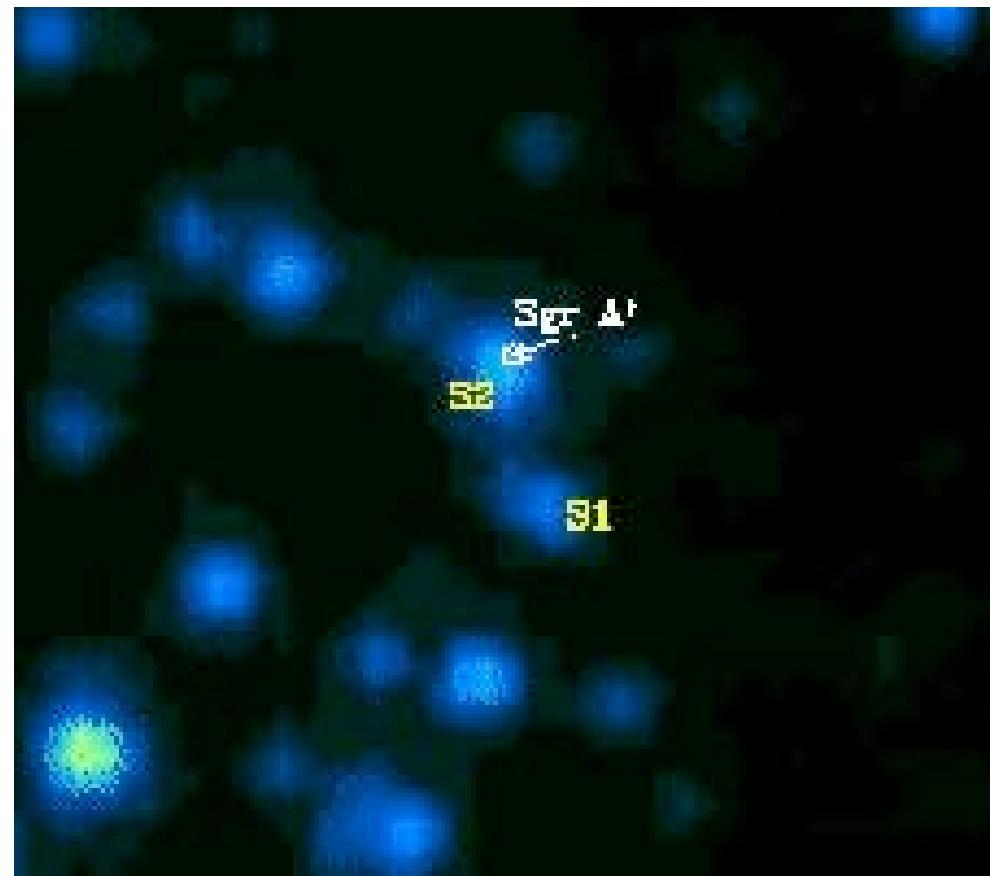


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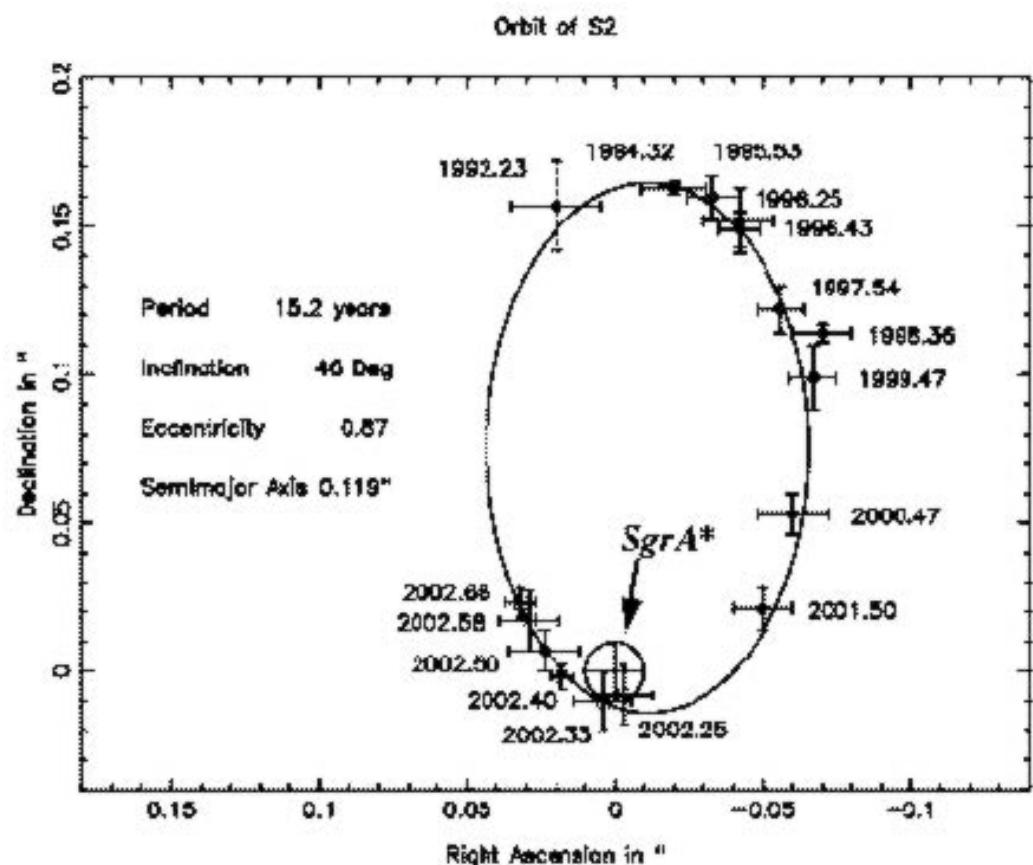
# Where was Sgr A\* in 2002

- Sgr A\* position: 10 mas  
Reid et al (2003)
- Star "S2"  
seen at pericenter passage  
 $V \sim 5000$  km/s !!  
Orbit determined  
Schoedel et al (2002)



# S2's orbit

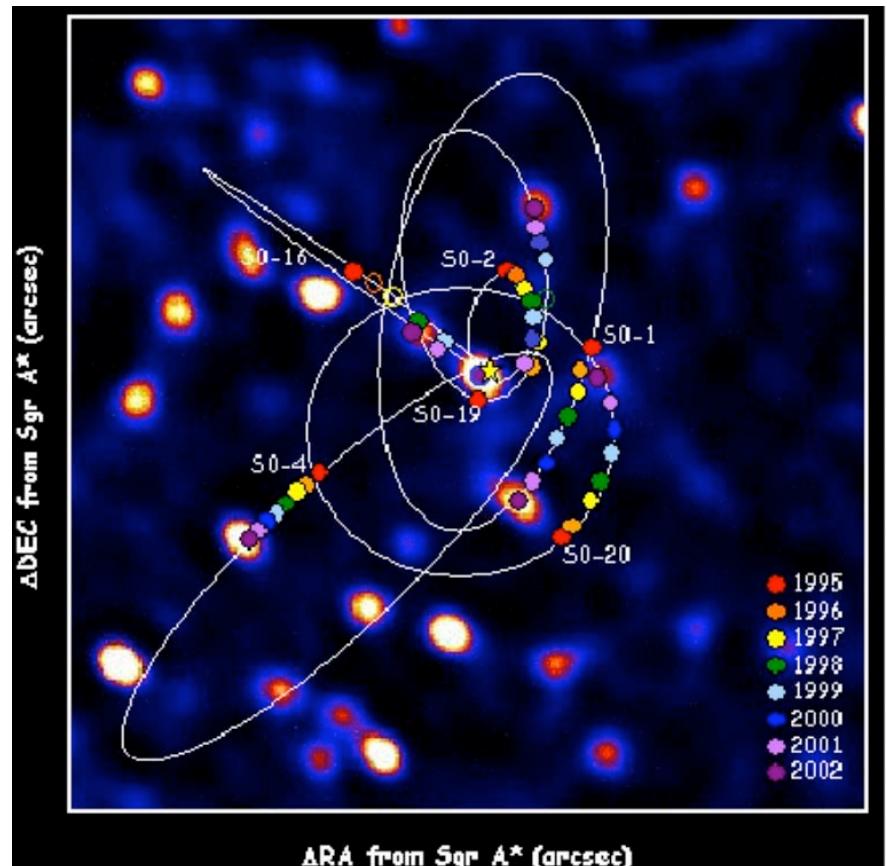
- 15 year period
- $e = 0.87$
- Pericenter only 15 mas from Sgr A\* !  
( $120 \text{ AU} = 17 \text{ l-h}$ )



(Schoedel et al 2002)

# Stellar Orbits

- 5 stars with orbits
- Enclosed mass:  
 $4 \times 10^6 M_{\text{sun}}$   
within 100 AU radius
- Sgr A\* within 80 AU of orbital focii



Ghez et al

# Question 1:

- Is Sgr A\* at the center of the stellar cluster?  
Yes... to better than 10 mas (80 AU)

# Must Sgr A\* be a SMBH?

- IR stellar orbits:  $4 \times 10^6 M_{\text{sun}}$  in 100 AU  
Is this mass in a SMBH and must Sgr A\* be that SMBH?
- Gravitational mass = Radiative Source?  
Orbital focii = Sgr A\*'s position (10 mas = 80 AU)  
Short dynamical cluster lifetime
- Problems...  
Sgr A\* exceedingly underluminous (<LMXB !)  
Can cluster lifetime problem be avoided by resupply?

# Radio/IR frame alignment

- Compare Radio(SiO) and IR **positions**:
- Compare Radio(SiO) and IR **motions**:  
SiO maser motions relative to Sgr A\*  
Tie IR motions to Sgr A\*

# Velocity Alignment

East,North proper motions in mas/yr

Star	Radio	Infrared	Difference
IRS 9	+3.6,+2.4	+2.0,+0.5	+1.6 (0.7),+1.9 (1.2)
IRS 7	-1.6,-4.5	-0.8,-3.6	-0.8 (1.0),-0.9 (3.5)
IRS 12	-0.8,-2.8	-3.3,-0.8	+2.4 (0.5),-2.0 (0.8)
IRS 10	+0.2,-2.1	+0.1,-2.2	+0.1 (0.4),+0.1 (1.0)
Unweighted mean (sem)		+0.8 (0.8),-0.25(1.0)	

1 mas/yr  $\sim$  40 km/s

- Central star cluster moves with Sgr A\* to  $\sim$ 70 km/s

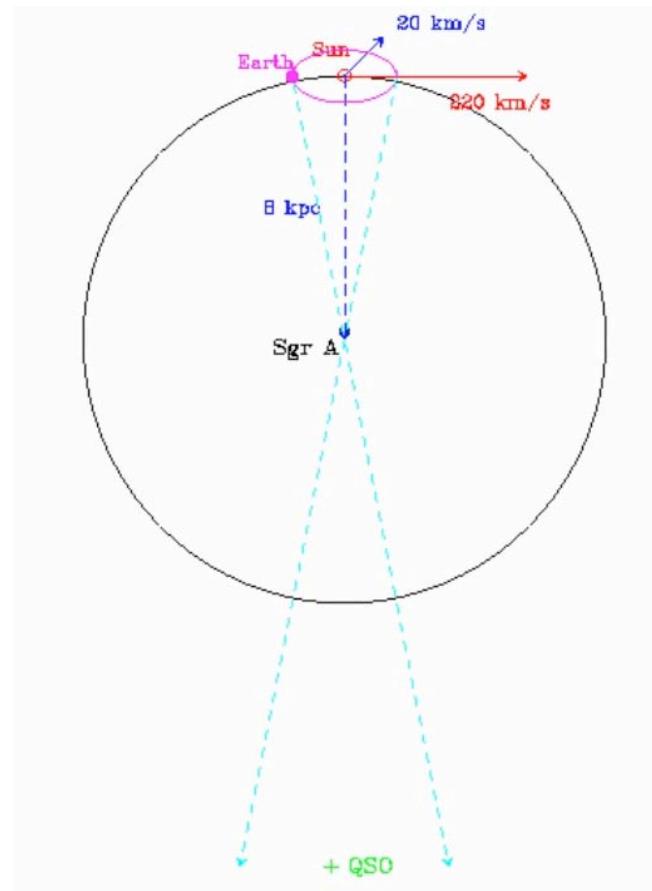
# Question 2:

- Is the stellar cluster tied to Sgr A\*?  
Yes... to better than 70 (35) km/s

# Proper Motion of Sgr A\*

Sun's Galactic Orbit:

- 225 Myr period
- 220 km/s @ 8.0 kpc  
= 6 mas/yr

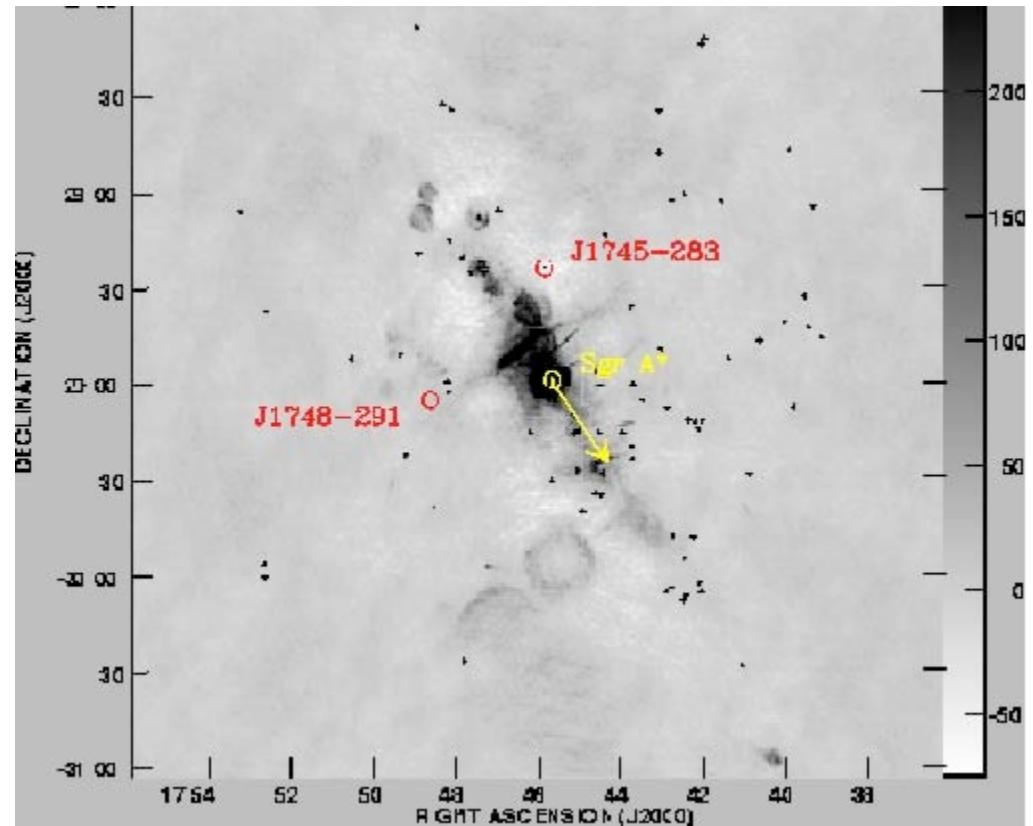


# Project History

- 1979: Proposal to US VLBI Network
  - “To Study Feasibility of Detecting Proper Motion of the Galactic Center”
  - 15 GHz; OVRO, HRAS, GB, Haystack
  - Failed:
    - Scatter broadened Sgr A\*
    - Limited sensitivity
- Needed VLBA !

# Sgr A\*'s apparent motion

- Relative to 2 Quasars
- Sun's Galactic Orbit:  
220 km/s at 8.0 kpc =  
6 mas/yr in Gal plane

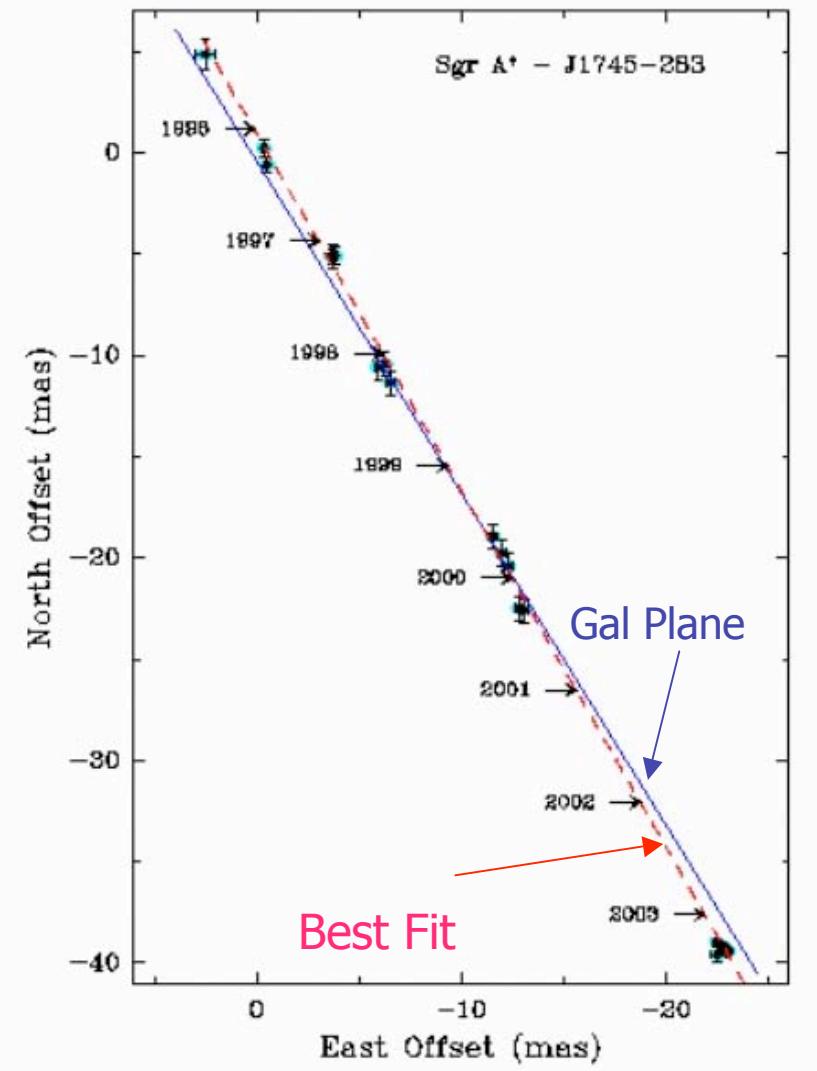


(Kassim, Frail & Briggs)

# Sgr A\*'s Apparent Motion

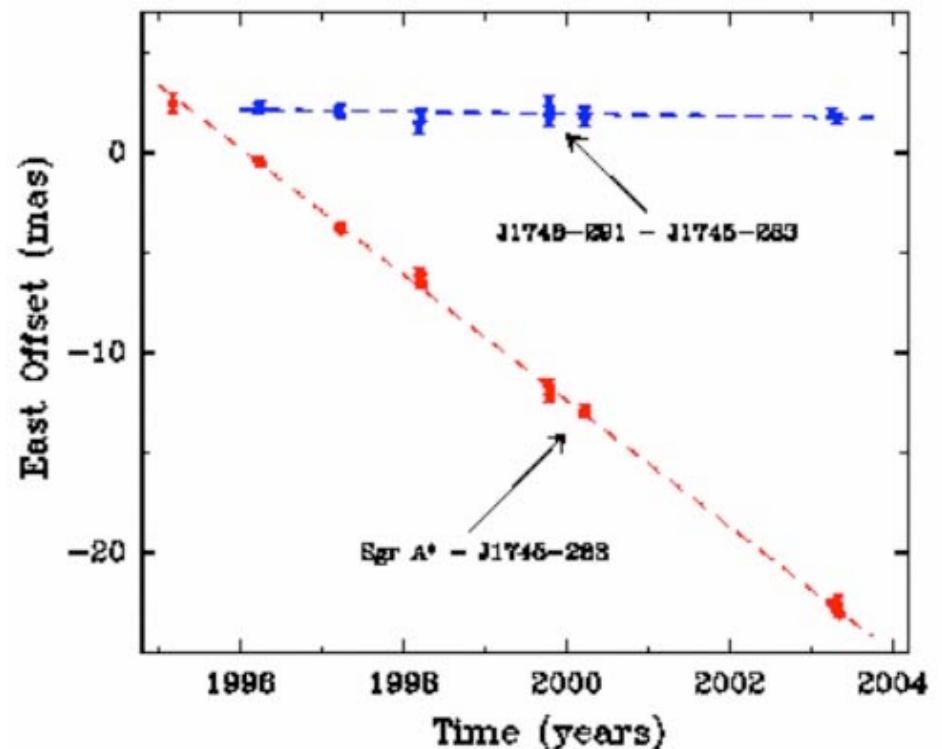
VLBA results:

- Moves mostly along Galactic Plane
- Slight deviation from  $V_{\text{SUN}}$



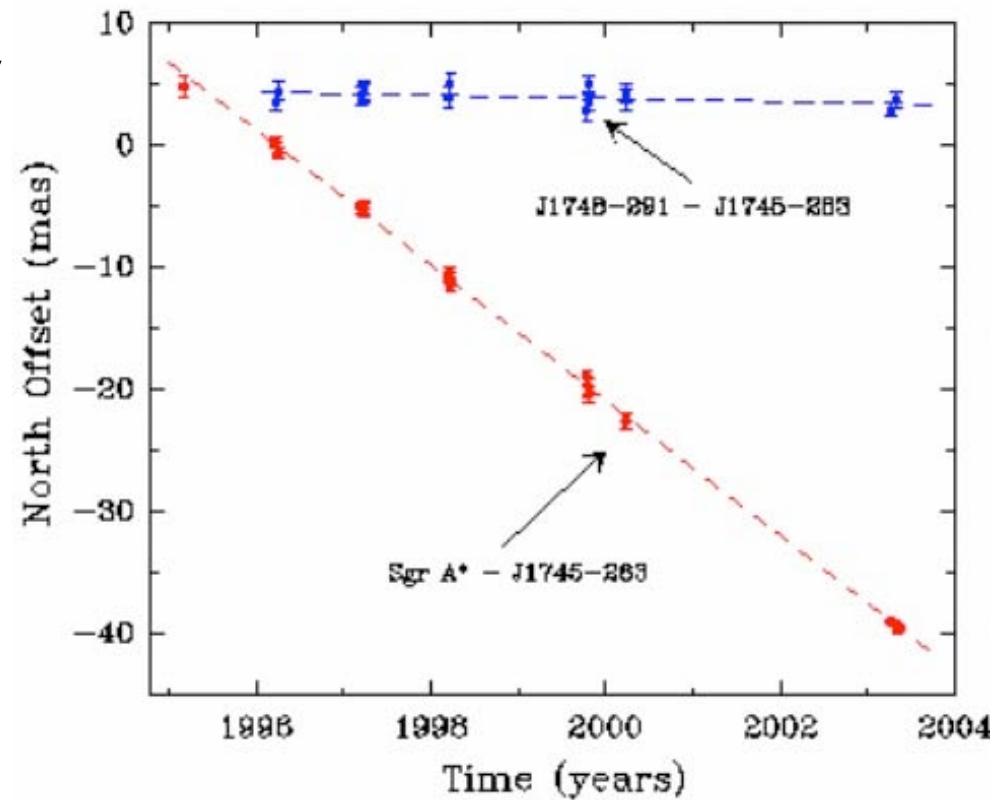
# Eastward Motion

- Sgr A\* drifts smoothly
- QSOs don't move



# Northward Motion

- Sgr A\* drifts smoothly
- QSO don't move
- NB: error bars larger than eastward positions



# Sgr A\* motion Galactic Coords:

- Motion in Galactic Plane:

$$\Theta_0/R_0 = 29.4 \pm 0.2 \text{ km/s/kpc}$$

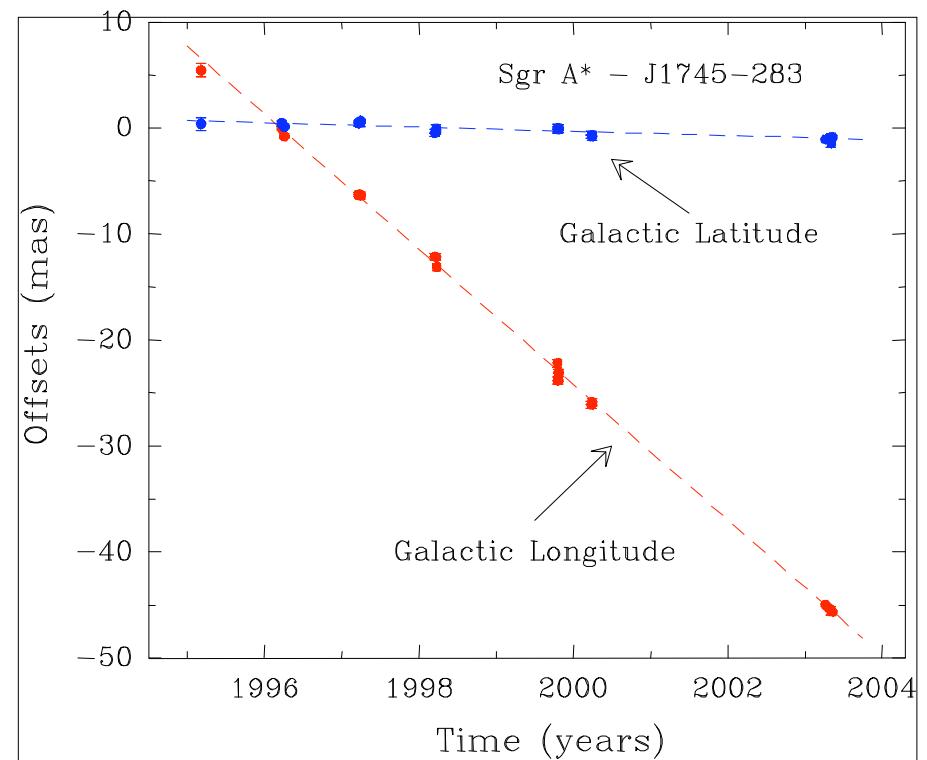
Compare to

$$(A-B)/R_0 = 27.2 \pm 0.9 \text{ km/s/kpc}$$

(Feast & Whitelock 1997)

- Motion out of Galactic Plane:

Very small...



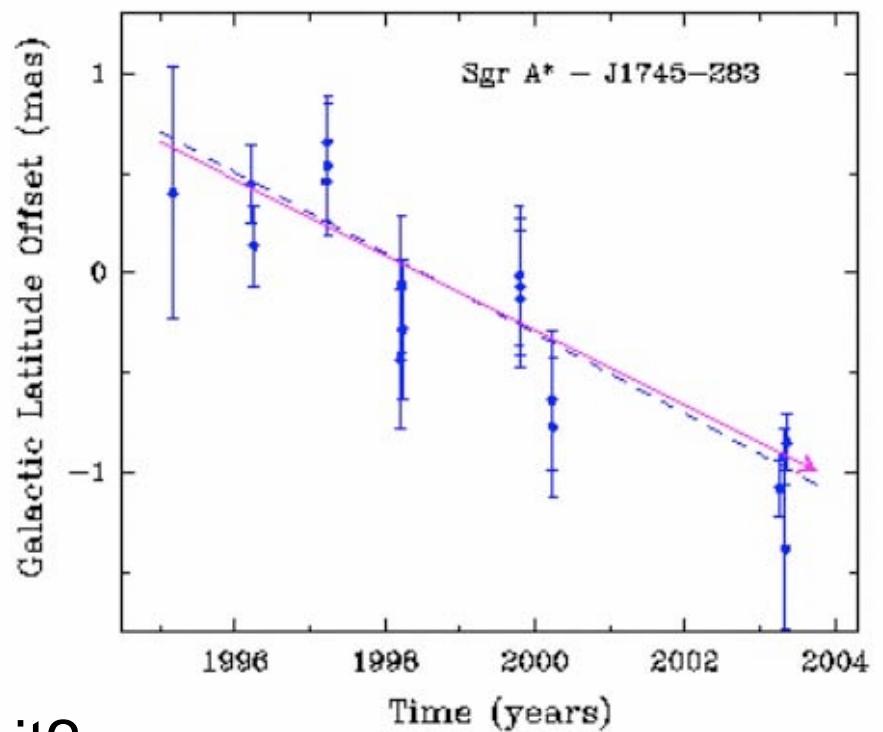
# Question 3:

- Is Sgr A\* at the dynamical center of the Galaxy?  
Yes... to within our knowledge of  $\Theta_0/R_0$

# Sgr A\* motion toward Galactic Pole

- Solar Motion 7.2 km/s
- Sgr A\*'s peculiar motion  
-0.4 +/- 0.9 km/s
- Sgr A\* must be massive!

Can we quantify a mass limit?



# Question 4:

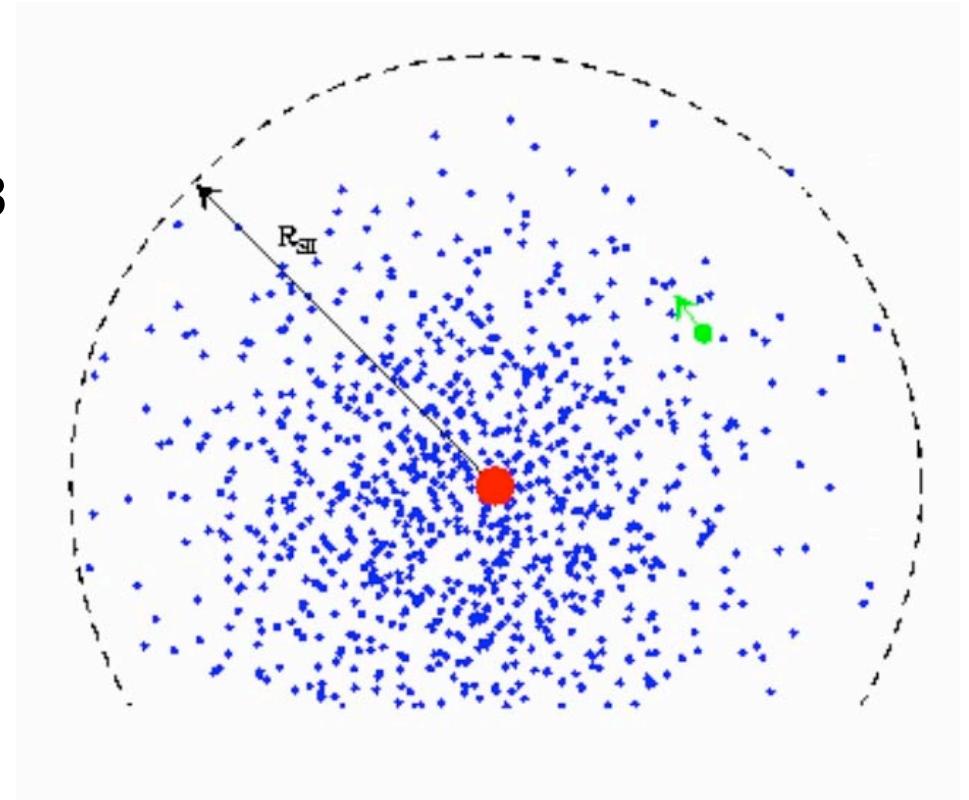
- Does Sgr A\* have a peculiar motion?  
No ... less than 1.8 km/s (out of Plane)

# BH Brownian motion:

- Chatterjee, Hernquist & Loeb 2002
- Dorband, Hemsendorf & Merritt 2003
- Reid & Brunthaler 2004
- Laun & Merritt 2004

$$V \sim 0.17 \text{ km/s} m^{1/2}$$

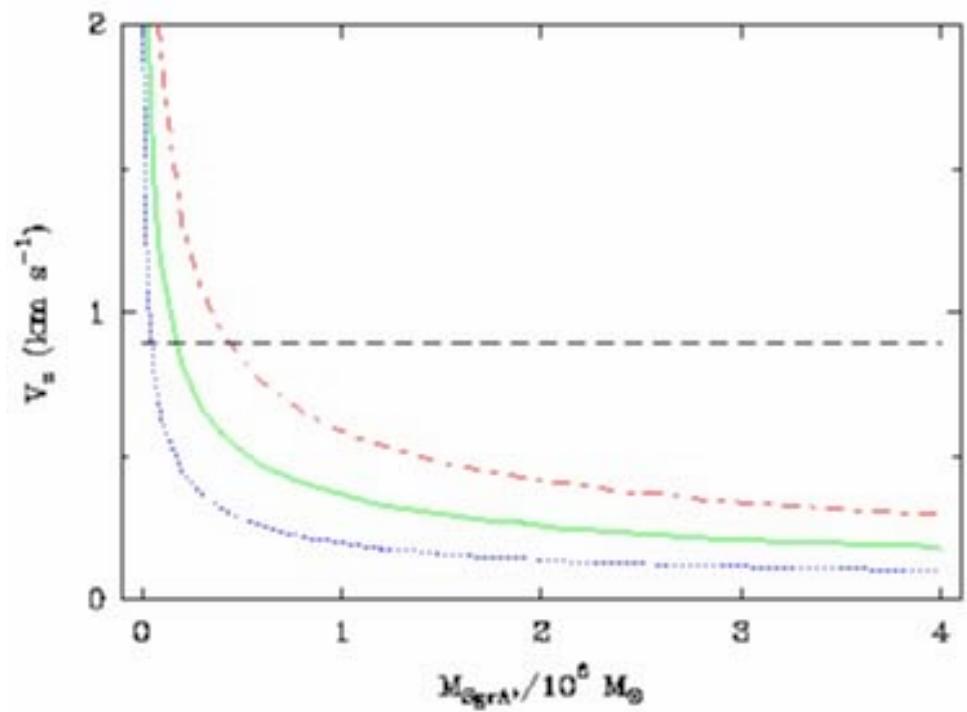
$$M(\text{SgrA}^*) > \sim 10^5 M_{\text{sun}}$$



# Effect of Bound Stars on Sgr A\*

Recipe:

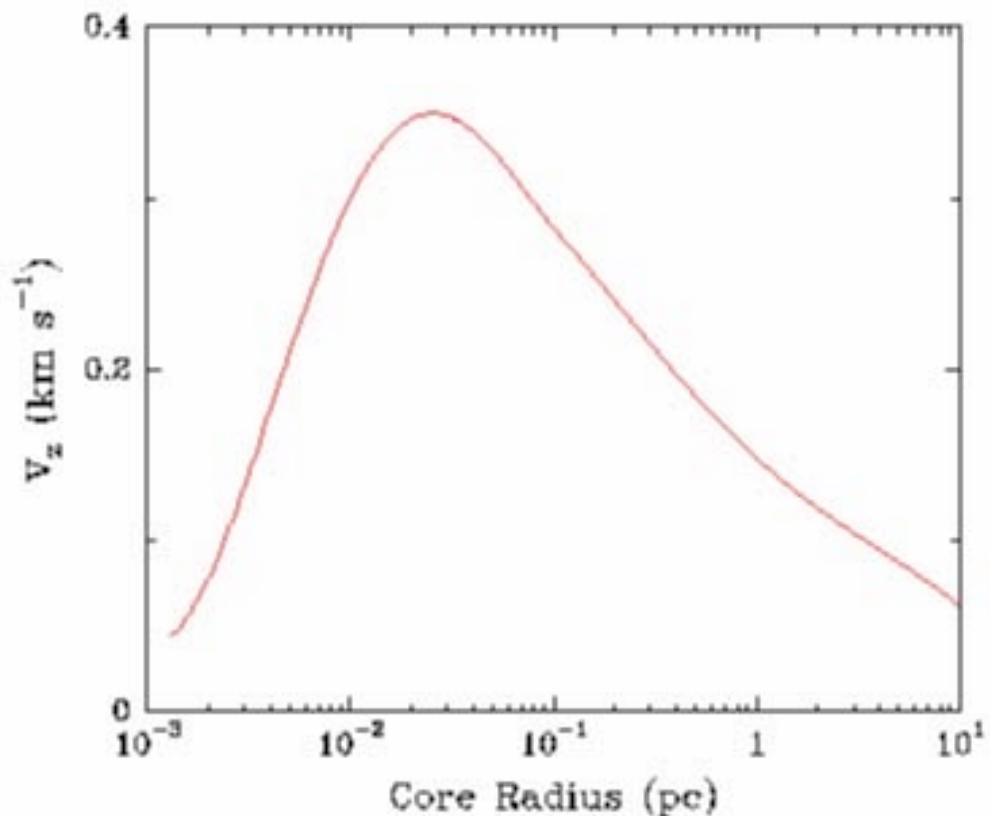
1. Put  $4 \times 10^6$  stars in computer
2. Place SMBH at center of mass of system
3. Solve Kepler's Eq for each star
4. Calculate COM after 8 years
5. Determine position & then velocity of SMBH
6. Repeat as needed to get  $V_{\text{rms}}$



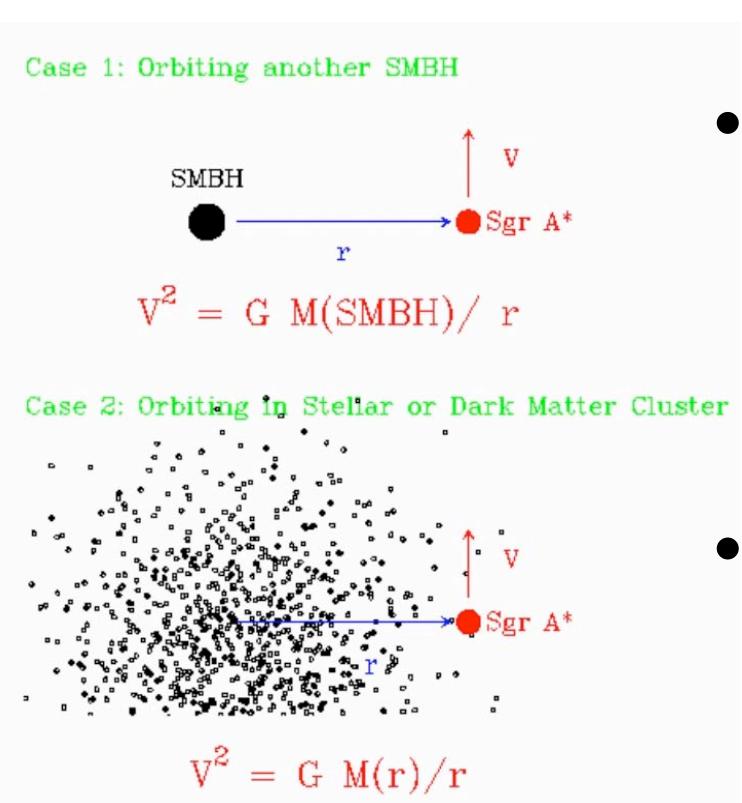
For 3 different stellar IMFs

# Cluster of Stellar Remnants

- Expect stellar remnants in G.C.
- IR stellar orbits allow  $10^5$  remnants  
(Mouawad, Eckart, et al 2003)
- Calc: effect of  $5 \times 10^4$  with varying core-radii
- $V_z \sim 0.3$  km/s possible  
Comparable to observed stars!



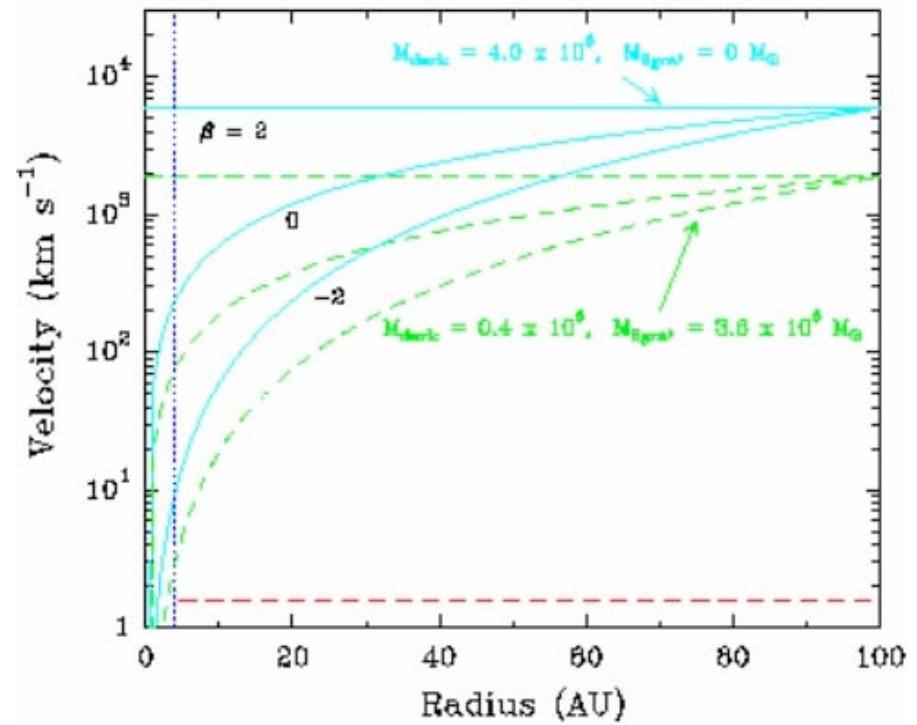
# If Sgr A\* is not a SMBH...



- 1) Tight binary black hole  
Decays by Grav Radiation  
 $T \ll 10^6 \text{ yr}$
- 2) Theoretically “flexible”  
eg, density power law:  $\rho \sim 1/r^\beta$

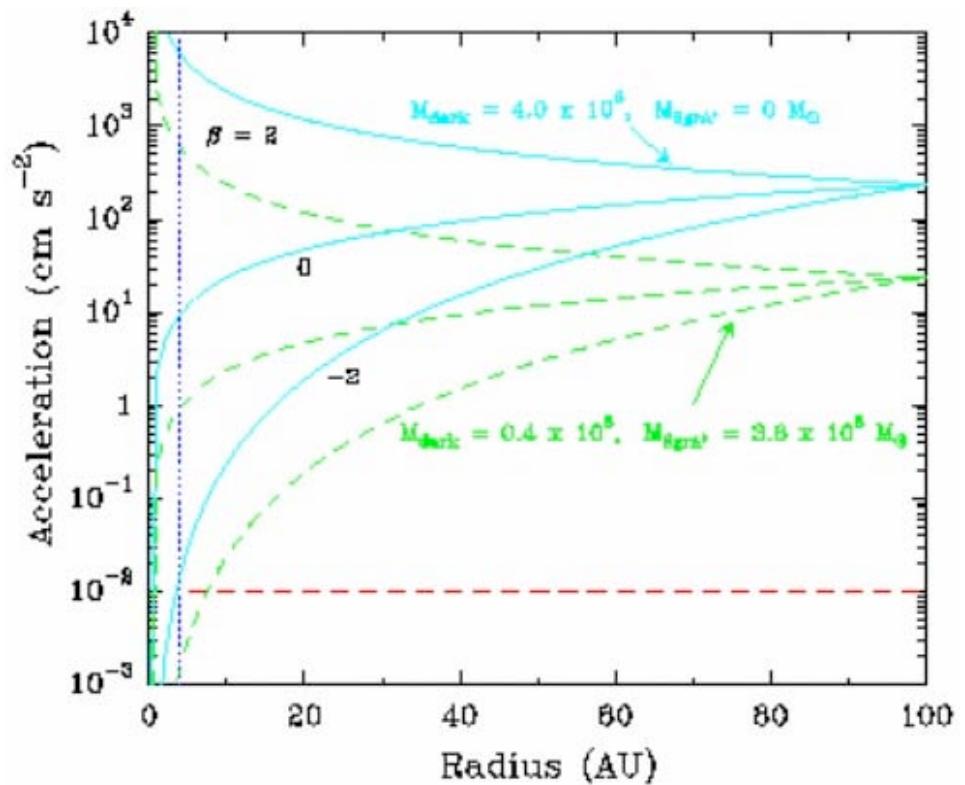
# If Sgr A\* is not a SMBH...

- $V \gg 1$  km/s for any dark matter distribution, unless  $M_{\text{dark}} \sim 0$



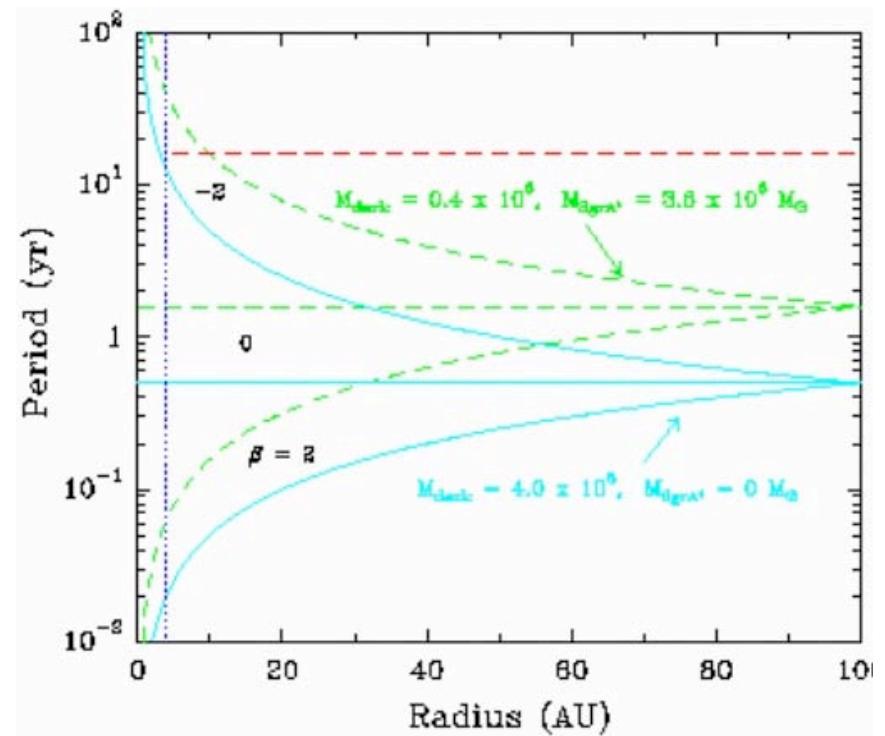
# If Sgr A\* is not a SMBH...

- Accel  $>> 10^{-2}$  cm/s<sup>2</sup>
- Would be easily observed, EXCEPT...



# Sgr A\* “orbital period”

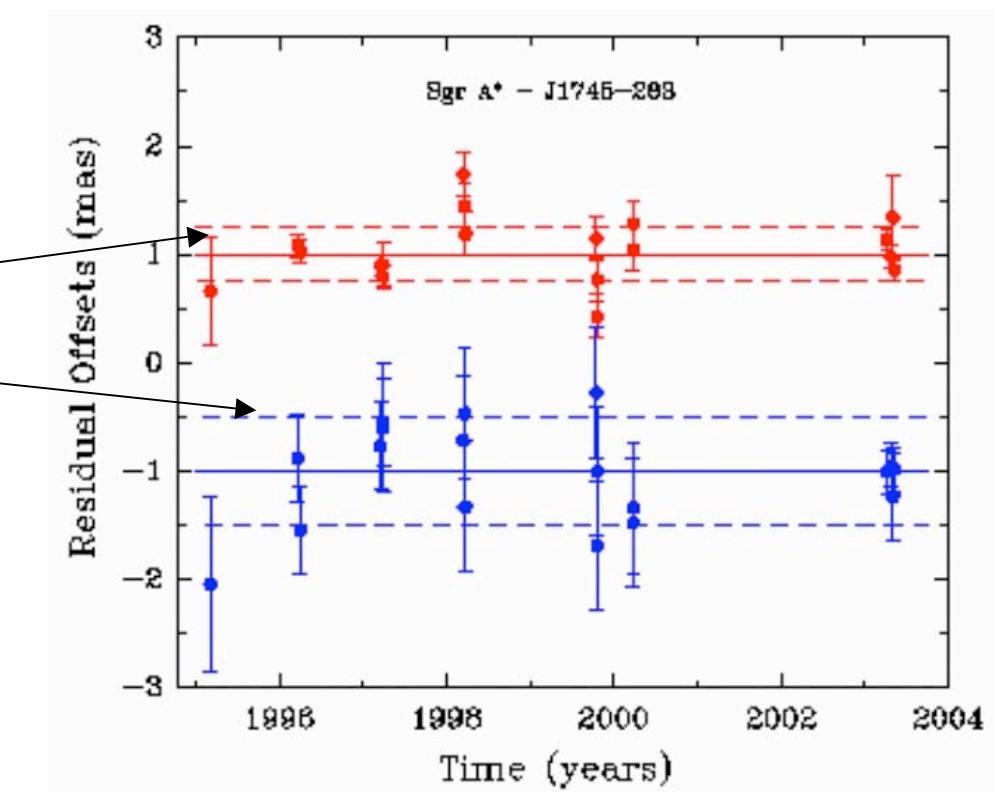
- Measured V (& A) not sensitive to  $P < 16$  yrs
- Essentially all dark mass distributions give  $P < 16$  yrs



But, all is not lost...

# Were Sgr A\* tightly bound to something in GC, could it escape detection in our VLBA observations?

- Would easily see position excursions:
  - >0.25 mas (2 AU) in RA,
  - >0.50 mas (4 AU) in Dec
- Sgr A\* must either be
  - i)  $\sim 4 \times 10^6 M_{\text{sun}}$
  - ii) “bound” within 4 AU



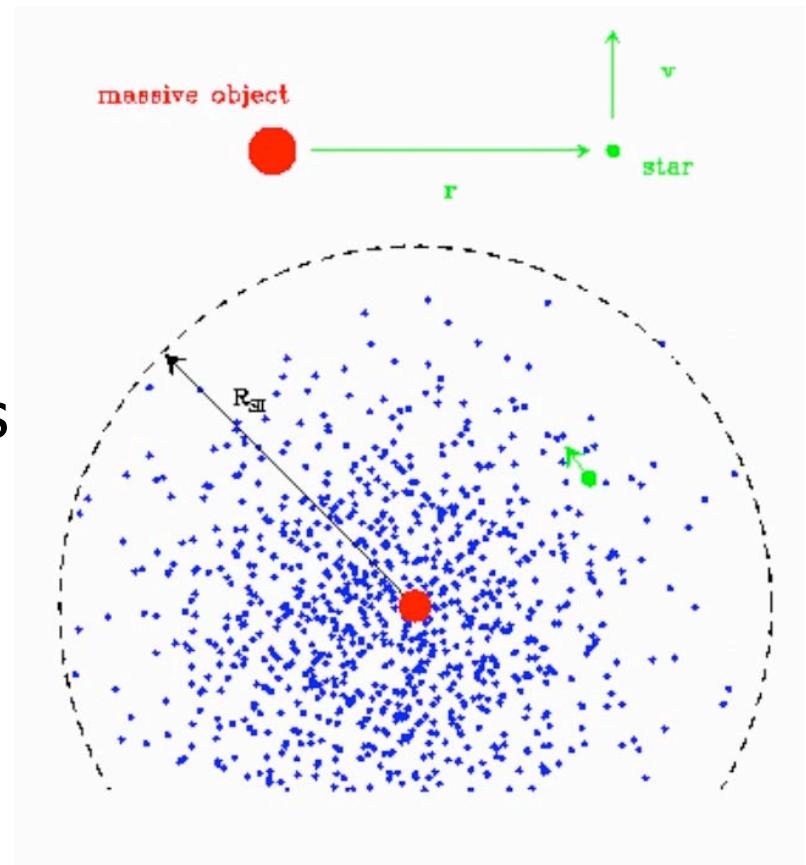
# Stars orbiting Sgr A\*

- Consider star orbiting a massive object:

$$MV = mv$$

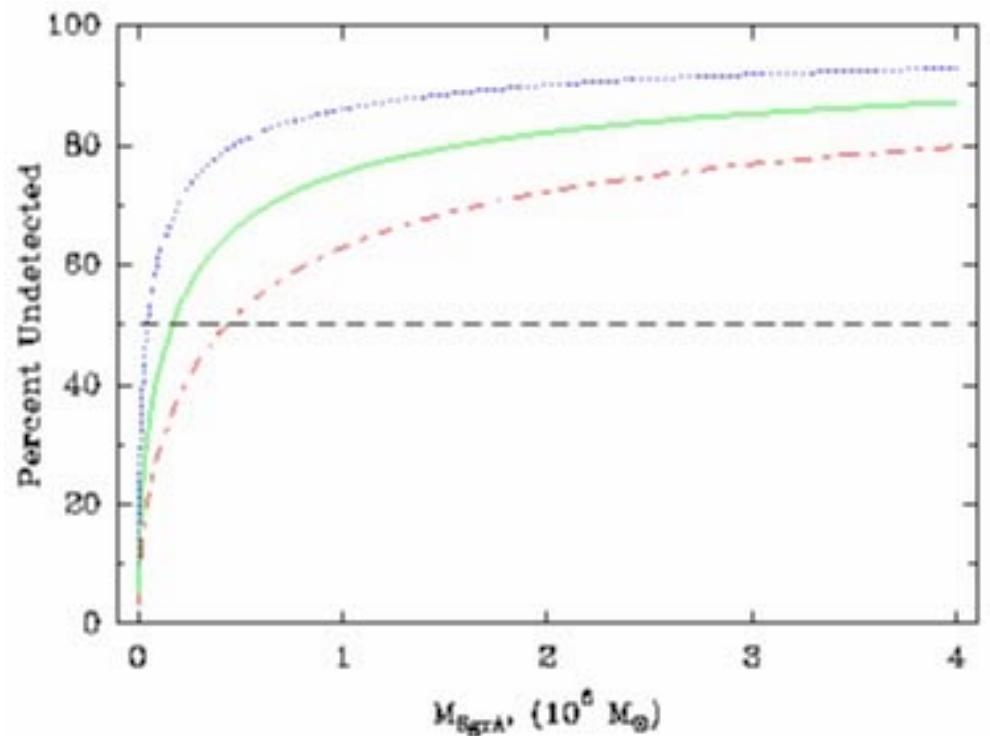
- Add in large number of stars & random fluctuations give:

$$MV^2 \sim mv^2$$



# Sgra A\* must be massive...

- Compare simulated systems with trial measurements
- Sgr A\*'s mass ( $M_{\text{sun}}$ )
  - Best est.:  $>0.4 \times 10^6$
  - 90% conf.:  $\sim 10^4$
- Very conservative calc.:  
Ignored effects of DM,  
clumping, stars  $> 2$  pc



# Question 5:

- Does Sgr A\* have all the gravitational mass?  
Probably ... current est.  $>10\%$  of  $4 \times 10^6 M_{\text{sun}}$

# Bayesian Approach: Laun & Merritt (2004)

- Expected Vz of 0.1 km/s
- Median value Vz < 0.9 km/s is  $10^5 M_{\text{sun}}$

# Dark Matter:

- Could exotic dark matter dominate the G.C. mass?  
Not likely...  $>10^5 M_{\text{sun}}$  within 4 AU hard to do
- Tied radiative source to the mass...  
“Fermion ball” probably can’t give Sgr A\*’s SED
- First time a large mass tied **directly** to an AGN (radiative source)

# Intermediate Mass Black Holes:

- SMBH (Sgr A\*) – IMBH “binary”:

$$V_{\text{SgrA}} \sim (M_{\text{IMBH}}/M_{\text{SgrA}}) V_{\text{IMBH}}$$

$$\sim 1.5 \text{ km/s} (M_{\text{IMBH}}/10^4 M_{\text{sun}}) / (r/10^4 \text{ AU})^{1/2}$$

- Combining orbital excursions and velocity of Sgr A\*, intermediate mass black holes constrained:

$M < 10^4 M_{\text{sun}}$  for  $10^3 < r < 10^5 \text{ AU}$  ( $\sim 0.005\text{-}0.5 \text{ pc}$ )  
(Hansen & Milosavljevic 2003)

- Caveat: Only for motion out of Galactic plane.
  - IRS 16 SW out of plane
  - IRS 13 near plane, but motion not in plane

# 7 Questions: 7 Answers

- Is Sgr A\* at the center of the stellar cluster?  
Yes ... to within 10 milli-arcsec
- Is the stellar cluster tied to Sgr A\*?  
Yes ... to within 70 km/s
- Is Sgr A\* at the dynamical center of the Galaxy?  
Yes ... to within our knowledge of  $\Theta_0/R_0$
- Does Sgr A\* have a peculiar motion?  
No ... less than 1.8 km/s
- Does Sgr A\* have all the mass sensed by stars?  
Probably ... ( $>10\%$  and “rising”)
- Could exotic dark matter dominate the G. C. mass?  
Not likely ... (density too extreme; can’t give SED)
- Can intermediate mass black holes exist in G. C.?  
IMBHs  $> 10^4$  Msun unlikely between 0.005 – 0.5 pc

# Must Sgr A\* be a SMBH?

Object	Density ( $M_{\text{sun}}/\text{pc}^3$ )	Method	Mass & Radius
M 87	$2 \times 10^6$	HST:	$3 \times 10^9 M_{\text{sun}}$ in 7 pc
NGC 4258	$7 \times 10^9$	VLBA : H <sub>2</sub> O	$3 \times 10^7 M_{\text{sun}}$ in 0.1 pc
Sgr A*	$2 \times 10^{17}$	S2's orbit	$4 \times 10^6 M_{\text{sun}}$ in 45 AU
Sgr A*	$2 \times 10^{19}$	excursions	$4 \times 10^6 M_{\text{sun}}$ in 4 AU
Sgr A*	$7 \times 10^{21}$	proper motion	$4 \times 10^5 M_{\text{sun}}$ in 0.5 AU
SMBH	$2 \times 10^{25}$	$R_{\text{sch}}$	$4 \times 10^6 M_{\text{sun}}$ in 0.08 AU
			$(10 \mu\text{as} @ 8\text{kpc})$

VLBI (eg, SMA-ALMA-LMT-CARMA...) @ 1 mm -> 20 uas

# The Ultimate Proof/Prize

- Image SMBH with resolution  $\sim R_{\text{Sch}}$
- Show all of the mass is contained within  $\sim 3R_{\text{Sch}}$
- See how accretion disk, black hole, and jets work
  - eg, image during a GLAST flare

